

Turbulence in Wind-Blown Bubbles around Massive Stars

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Abstract.

Winds from massive stars (> 8 solar masses) result in the formation of wind-blown “bubbles” around these stars. In this paper we study, via two-dimensional numerical hydrodynamic simulations, the onset and growth of turbulence during the formation and evolution of these wind-blown “bubbles”. Our simulations reveal the formation of vortex rolls during the Main-Sequence stage of the evolution, and Rayleigh-Taylor instabilities in the subsequent stages due to accelerating and/or decelerating wind-blown shells. The bubble shows a very turbulent interior just prior to the death of the star, with a significant percentage of the internal energy expended in non-radial motions. This would affect the subsequent evolution of the resultant supernova shock wave. We discuss the implications of these results, show how the ratio of kinetic energy in radial versus non-radial motions varies throughout the evolution, and discuss how these results would carry over to three dimensions.

PACS numbers: 94.05.Lk, 95.30.Lz, 97.10.Fy, 97.10.Me, 97.60.-s

1. Introduction

Mass loss from stars is a ubiquitous process. During their lifetime, stars lose mass mainly via stellar winds. These winds may be driven by coronal pressure in stars like the sun, by radiation pressure on dust grains such as in Asymptotic Giant Branch stars, or by radiation driving due to line or continuum opacity in massive stars (for further details see Lamers and Casinelli 1999). Mass loss via winds is mainly characterized by the mass-loss rate and velocity of the wind, and these parameters may change continuously throughout the stellar lifetime (Garcia-Segura et al. 1996; Langer et al. 1994).

The interaction of the wind from the star with the ambient medium leads to the formation of wind-blown “bubbles”. The structure and morphology of these wind-blown bubbles was first elucidated in a seminal paper by Weaver et al. (1977), and has been explored by several authors since. While the model has been hugely successful in explaining the global structure of wind-blown bubbles, the finer details can only be explored by multi-dimensional numerical simulations. These have been carried out by several authors (for recent results see Freyer et al 2006; Arthur 2007; Dwarkadas 2007b; van Marle et al 2007). These authors have examined various different aspects of the problem. The first two included the ionization from the star in their numerical calculations, but assumed that the wind parameters were constant in the various phases. Dwarkadas (2007b) did not include the effects of stellar ionization, but took into account the continuous variation of the wind parameters by adopting them directly from the output of a stellar evolution code. Unlike a previous calculation (Garcia-Segura et al. 1996), Dwarkadas (2007b) ran the simulations in 2-dimensions from the beginning. In order to take the evolution in the wind parameters into account accurately, the simulation was run for almost 2 million timesteps, one reason why it is computationally intensive to include the time evolution along with the ionization effects.

The variation in the wind parameters results in considerable turbulence within the bubble interior, which was not seen in the work of Arthur (2007) and Freyer et al. (2006) as they assumed average (and constant) wind parameters in each stage of evolution. In Dwarkadas (2007b) we touched upon some aspects of this turbulence, but concentrated mainly on the hydrodynamical aspects of the wind-bubble evolution and the subsequent evolution of a SN shock wave within the wind bubble. In this companion paper we explore in more detail the formation and growth of turbulence within the wind blown bubble, and the implications for the subsequent evolution, the emission from the bubble and observations of wind-blown bubbles, and future 3D simulations. Our aim is not to explore the quantitative aspects of turbulence or derive energy spectra. In keeping with the objectives of the conference where this work was presented, they are to explore the manifestation of turbulence and turbulent mixing mechanisms in wind-blown bubbles around massive stars, accentuate the factors that lead to turbulence in these conditions, and explore its effects on the hydrodynamics and subsequent evolution.

The rest of this paper proceeds as follows: In §2 we describe the basic structure and evolution of a wind blown bubble. In §3 we give a brief description of wind-blown

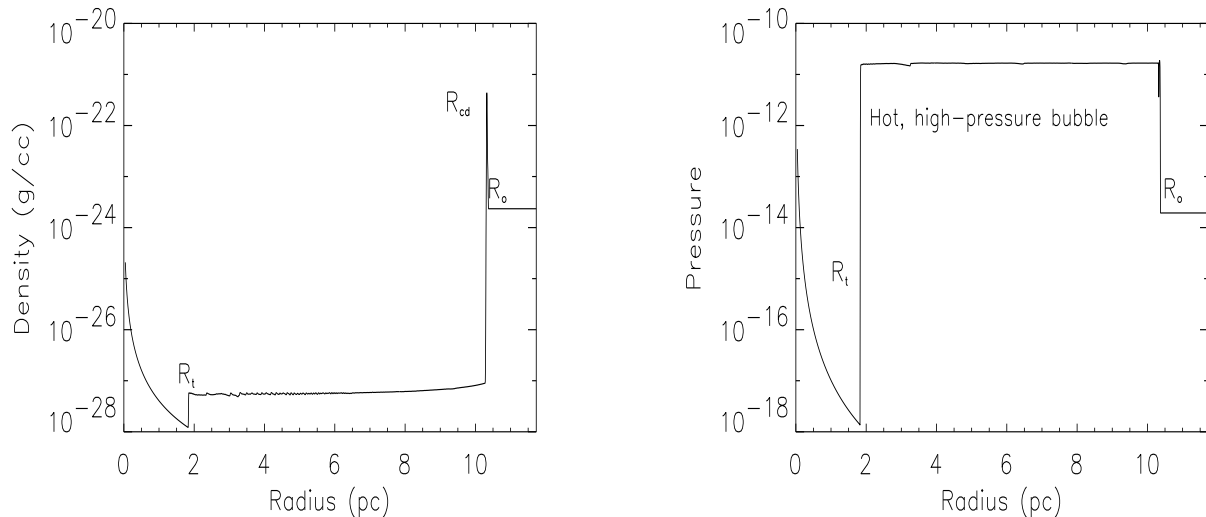


Figure 1. a) Density and b) Pressure profiles from a numerical simulation of a wind-blown bubble around a massive star.

bubbles around massive stars. In §4 we examine in detail the various manifestations of turbulence that we see in our simulations. Finally §5 discusses the implications of our results and prospects for future work.

2. The Structure of a Wind-Blown Bubble

The general structure of a wind-blown nebula was first elucidated by Weaver et al. (1977). In the simplest, two-wind approximation, a fast wind from a star collides with slower material emitted during a previous epoch, driving a shock into the ambient medium. The pressure of the post-shock material causes the freely flowing fast wind to decelerate, driving a second shock that propagates into the wind. A complex double-shocked structure is formed, separated by a contact discontinuity. Figure 1 shows the density and pressure profiles from a simulation of a wind-blown bubble. Going outwards in radius from the central star we find the following regions delineated: freely flowing fast wind, inner or wind-termination shock (R_t), shocked fast wind, contact discontinuity (R_{cd}), shocked ambient medium, outer shock (R_o) and unshocked ambient medium.

The shocked ambient medium is cooled and compressed into a thin, dense shell, which we will denote throughout as the circumstellar shell. Much of the volume of the bubble is occupied by a high pressure, low density region. The temperature within this region can be as high as 10^7 to 10^8 K. One would therefore expect significant X-ray emission from the bubble. However diffuse X-ray emission from nebulae surrounding massive Wolf-Rayet stars has been seen only in very few objects (Chu *et al* 2006).

The assumption of constant wind properties is not a very good one. As we have said before the wind properties, which can be thought of as a function of the stellar properties, evolve with the star. Evolving winds may change the basic structure considerably. In

particular, as we show in §4, they may introduce multi-dimensional effects such as the presence of hydrodynamic instabilities and the onset of turbulence (see also Dwarkadas & Balick [1998] for the planetary nebulae case). However even when the wind is evolving, as long as its mechanical luminosity ($0.5\dot{M}v_w^2$) remains constant, where \dot{M} is the mass-loss rate and v_w is the wind velocity, the above profiles will remain more or less valid. A major change in the pressure equilibrium is needed to alter the above profiles, which generally happens when stars go from one phase to another.

3. Brief Overview of Wind-Blown Bubbles around Massive Stars

Arthur (2007) has provided an elegant description of the formation of the wind-blown medium around a $40 M_\odot$ star, including the effects of the ionizing photons from the star. Dwarkadas (2005, 2007a,b,c) has summarized the properties of the bubble during various stages of the evolution and for stars of various initial masses. A wonderfully comprehensive review on the evolution of massive stars is given in Woosley et al. (2002). Herein we will only very briefly summarize some of these findings.

A massive star begins its life in the main-sequence (MS) stage, as an early type O or B star. These stars lose mass mainly through radiative driving, due to opacity in various lines. The wind has a mass-loss rate of about 10^{-8} to $10^{-6} M_\odot/\text{yr}$, and a wind velocity of 2000-4000 km/s. This is the longest, hydrogen burning phase, which can last for a few million years. The star will be expected to form a massive bubble upto several tens of parsecs in radius. As explained in §2, a double shocked structure is formed, with the inner shock generally only a few parsecs away from the center.

The subsequent evolution generally occurs within this bubble. Stars with solar metallicity will usually become red supergiants (RSG), once the hydrogen burning is completed. The star will swell up in size to greater than about 10^{13} cm, and begin to burn helium in the core. The large size implies a much smaller escape velocity off the surface of the star, and therefore a smaller wind velocity. RSG winds are assumed to be driven by radiation pressure on dust grains. The measured velocities are very slow, on the order of $v_w \sim 10 - 50 \text{ km s}^{-1}$, and the mass loss rates are quite high, approaching $\dot{M} \sim 10^{-4} M_\odot/\text{yr}$. Due to the low velocity, the RSG wind does not travel very far. The wind density (dependent on \dot{M}/v_w) is very high because of the low velocity, and thus it forms a high density region with a new pressure equilibrium. For constant wind parameters, the density decreases as r^{-2} .

Stars less than about $30\text{-}35 M_\odot$ will end their lives as RSGs. Stars greater than this mass may go on to form Wolf-Rayet (W-R) stars, which have very fast radiatively driven winds. Very massive stars ($> 50 M_\odot$) may also experience an unstable Luminous Blue Variable phase, wherein they eject a large amount of material over a short period of a few years, giving rise to an LBV bubble within the MS bubble.

Dwarkadas (2007b) completed a thorough study of the evolution of a $35 M_\odot$ star that starts off as a MS star, goes through the RSG stage and then forms a W-R bubble. We refer the reader to that paper (and Freyer et al. 2006) for a detailed

study of the hydrodynamics of the evolution. Herein, we will describe pertinent details of the hydrodynamics for the sake of completeness, while concentrating on aspects of turbulence that were not included in the earlier paper.

4. Turbulence in Wind-Blown Bubbles

In this paper we concentrate on two-dimensional simulations of the formation of wind-blown bubbles. These simulations were carried out with the VH-1 code, a 1, 2 and 3D numerical hydrodynamics code (see Blondin & Lundqvist [1993] for a more detailed description) that solves the equations of mass, momentum and energy conservation on a uniform grid. The calculations are carried out on a spherical $(r - \theta)$ grid in a Lagrangian frame, with the results at each timestep being remapped to the original Eulerian grid. Radiative cooling is included via a cooling function. A feature of this code is that it includes an expanding grid, which tracks the outer shock and expands outwards with it. This feature is exceptionally useful in situations such as the current one where the object being simulated expands almost 5 orders of magnitude

In our simulations of wind-blown bubbles we see various manifestations of turbulence. The initial **main-sequence stage** shows significant evidence of vorticity being deposited into the interior (shocked wind) region of the flow. This vorticity arises at the inner, wind-termination shock region. It is due to the slight change in the position of the termination shock (with respect to the outer shock and to its previous position) at every timestep, or every few timesteps. The change in the position leads to a change in the pressure and density just behind the wind termination shock. The post-shock flow, being subsonic, does not have enough time to equilibrate before the shock position changes again. This leads to continual changes in the pressure, which consequently leads to changes in the velocity and the development of a velocity gradient behind the inner shock. $\nabla \times v$ becomes non-zero, and vorticity is deposited within the interior flow.

Although it is clear why the position of the wind termination shock changes (due to changes in the wind properties), it is not as clear why the shape of the shock does. It is possible that this starts mainly from near the azimuthal axis, and is due to the so-called axis effect in a 2-D simulation. This is due to the fact that flow that is at an angle to the azimuthal axis is not allowed to cross the axis but is forced to slide along the axis in a 2-D calculation. The wind shock at the axis position is therefore extended or depressed, depending on whether the flow is moving away from the pole or towards it. The change in shape leads to changes in the radial density and pressure.

It is debatable whether such a situation would occur in the 3D case, when there is no artificial boundary and the flow would be able to cross the azimuthal axis. The important question however is whether a 3D situation would exist that would result in a wind termination shock that is not completely spherical. The answer to this is a qualified yes. The shape of the shock front responds to inhomogeneities in the flow, the presence of clumps and other density perturbations, or hydrodynamical instabilities. A case in point is the shock fronts seen in simulations of planetary nebulae (Dwarkadas

& Balick [1998], see Fig 2) where the shape of the shock front responds directly to finger-like clumps in the flow, and results in box-shaped inner shocks. As long as there is some entity capable of introducing instability within the flow, which is likely as long as the wind parameters are constantly changing, the result would be a distortion of the shock front and production of vorticity.

What is the result of this vorticity deposition? The vorticity is carried out with the shocked wind, and vortex rolls slowly fill the shocked wind. A snapshot of the velocity flow in the region is shown in Fig 2. The formation and clustering of vortices in the hot bubble is apparent. The vortices last for a long time, some of them lasting over the remaining main sequence lifetime since their birth. They also grow in size over the simulation. This is not visually apparent because the grid is expanding in size, but the fact that they retain their relative size as the grid grows over several orders of magnitude indicates the vortex growth. Thus, as is commonly seen in 2D simulations as opposed to the 3D case, the energy tends to cascade to longer wavelengths. There is a definite clustering of vortices, and vortex rolls near the axis tend to merge together. The overall effect is that some amount of energy is expended in non-radial turbulent motions.

In order to calibrate how much of the energy is expended in such motions, we calculated for each zone the kinetic energy per unit volume of non-radial motions, and divided by the total energy per unit volume. We find that a few percent of the energy, typically 3-5 %, is expended in non-radial motions, although at times it can instantaneously be up to 7-8 %. We also find that this fraction is more or less constant over varying resolution, showing that numerical resolution is not playing a large effect.

In the main sequence stage we see turbulence within the shocked wind. The onset of the **RSG stage** in our calculation leads to the development of a new pressure equilibrium and a thin RSG shell which is decelerated by the strong thermal pressure in the interior as it expands outwards. The decelerating shell is found to be unstable to the Rayleigh-Taylor (R-T) instability, and Rayleigh-Taylor fingers are seen developing that expand outwards from the high density gas into the low density external medium. This situation is shown in Fig 3, where density contours (grey shading) are shown overlapping the velocity vectors. Note that this phase lasts for a much shorter time, about 250,000 years, compared to the Main Sequence phase which last for about 4.5 million years. The presence of the R-T instability leads to some turbulence around the radius where the RSG material is piled up in a thin shell, but it is localized, and does not have sufficient time to grow because the duration of this phase is small.

The star then becomes a hot, blue, compact **Wolf-Rayet** (W-R) star. The wind velocity increases by almost two orders of magnitude, the mass-loss rate drops by a few, and the wind momentum therefore increases considerably. The W-R wind accelerates down the RSG density incline, the high pressure accelerating the dense W-R shell. The W-R shell is also therefore unstable to R-T instabilities with a very different Atwood number from the RSG case. However the dense region being accelerated is now exterior to the low density, high pressure region that is accelerating it. The R-T fingers therefore expand inwards from the dense shell into the interior of the W-R bubble. Our simulations

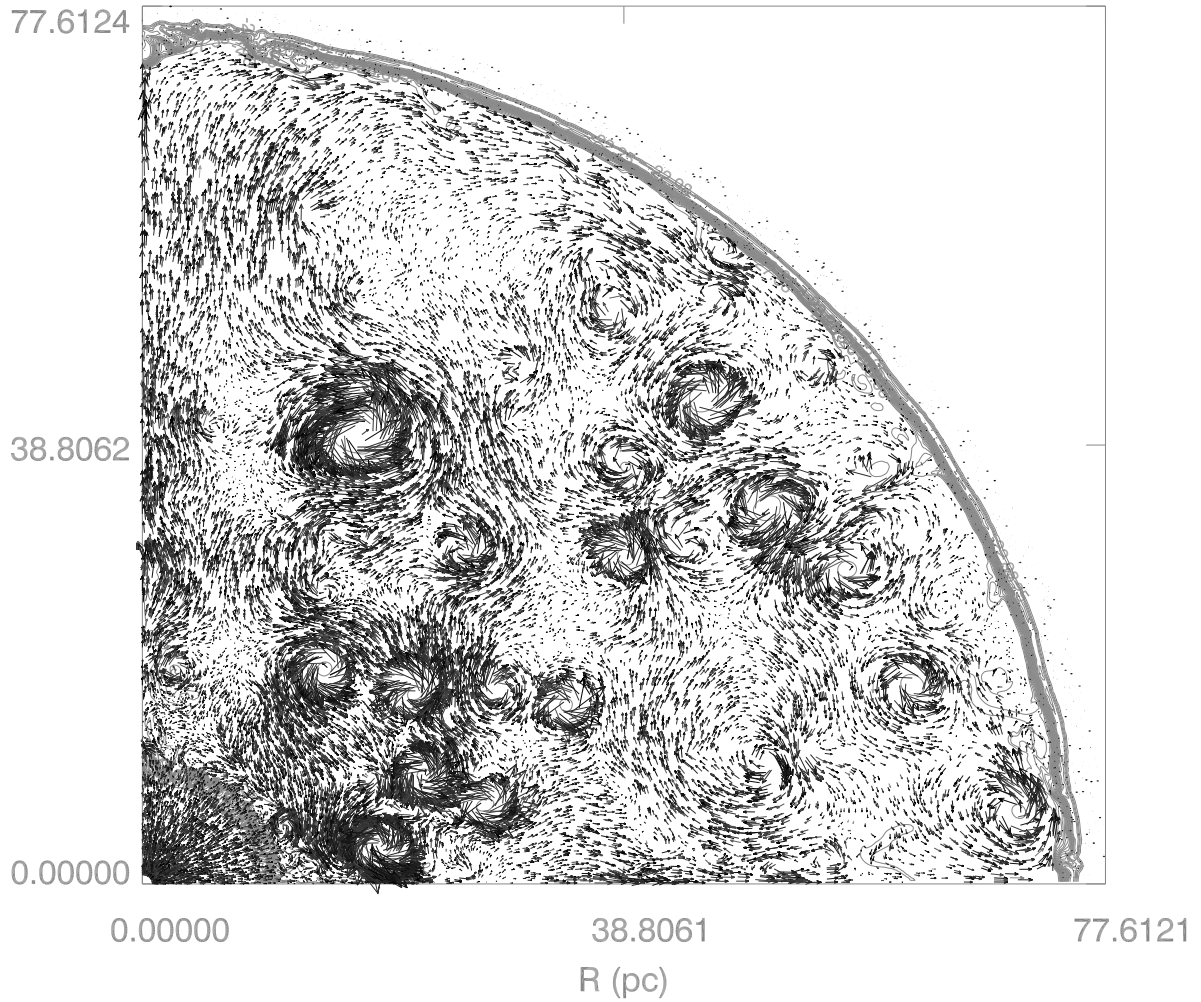


Figure 2. A snapshot showing the velocity contours during the main-sequence stage of the evolution of the wind-blown bubble. The formation and clustering of vortices in the shocked wind is clearly visible

clearly show the growth of inward-pointing protrusions in the W-R shell. Again however due to the smaller time period of the W-R phase (about 200,000 years) and the resolution of our simulations, the growth of the R-T fingers is limited.

The high momentum W-R wind succeeds in breaking up the RSG shell, which is already fragmented as described earlier, and distributing the material within the interior. The supersonic W-R material carries the RSG material along with it. However instead of a shell of material expanding out, it is a disjointed flow. Note that the amount of mass lost in the RSG stage is about 19.5 solar masses, while in the W-R stage it is only a couple of solar masses. So the high momentum W-R wind basically carries mostly RSG wind material. This material impacts the main-sequence shell and bounces back, but not in an ordered fashion, resulting in a highly turbulent medium at the end of the simulation. A snapshot of this medium just a few thousand years before the death of the

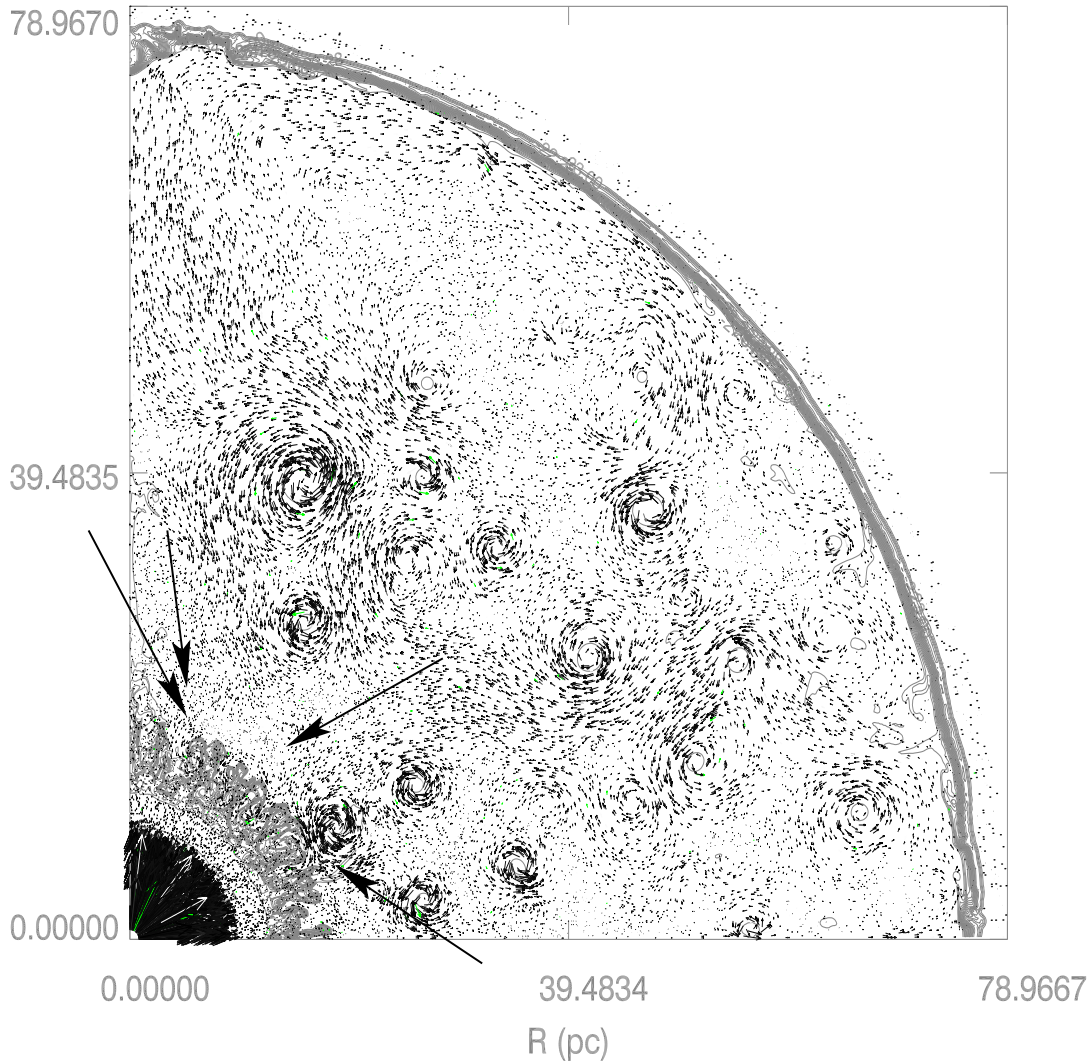


Figure 3. A snapshot showing the velocity contours during the red-supergiant stage of the evolution of the wind-blown bubble, with density contours superimposed. The arrows point to the Rayleigh-Taylor unstable thin shell of material, about 11pc from the center ($1 \text{ pc} = 3 \times 10^{18} \text{ cm.}$)

star is shown in Fig 4. The bounce of the W-R wind from the main-sequence shell, and the subsequent formation of an inner shock where the pressure of the wind equals the post-shock pressure behind the reflected material is seen. What is also apparent is the stirring up of the medium beyond the inner shock, due to the passage of the expanding W-R wind and the reflection from the outer shock.

The ratio of the energy in non-radial motions to that in radial motions is constantly changing throughout this evolution. In Fig 5 we show how the ratio of the energy in non-radial motions to that in radial motions varies through the simulation. We measure this ratio in the low density interior between the reverse shock and the contact discontinuity. For most of the MS phase the value is only 2-3%. Towards the end of the MS phase, the

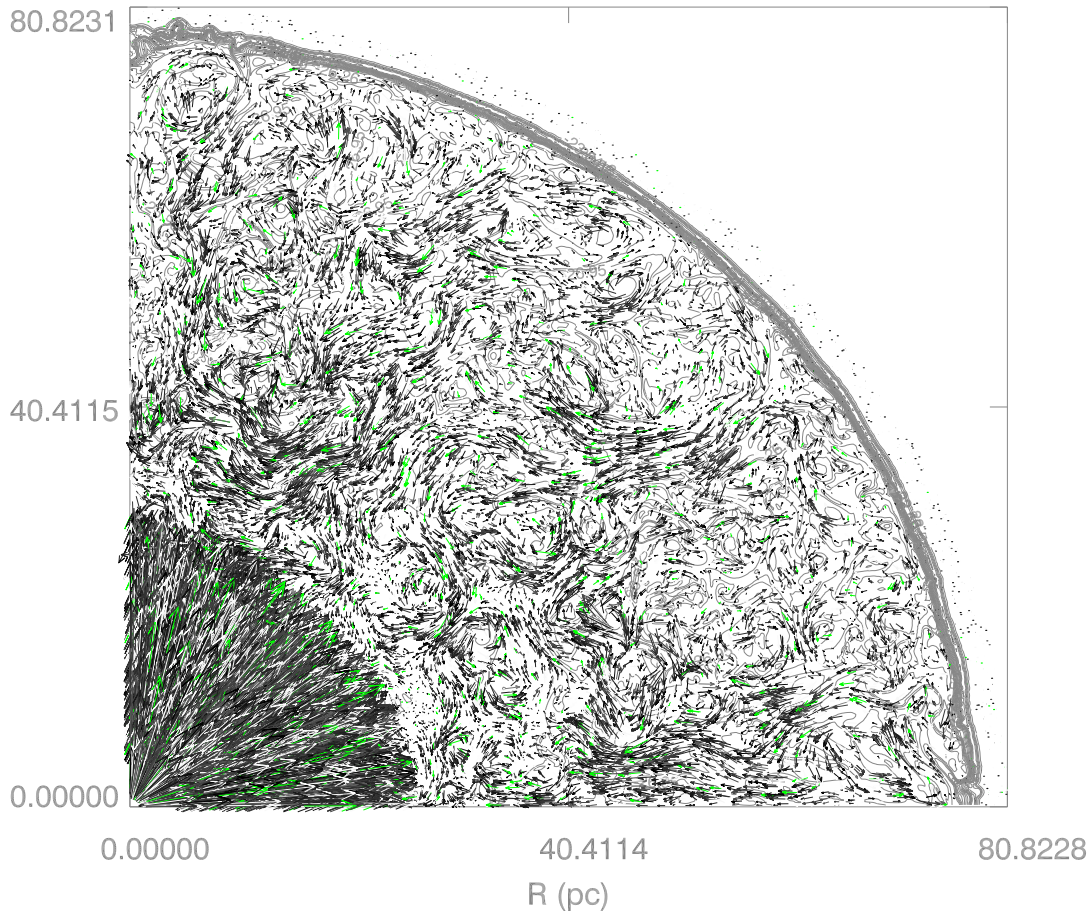


Figure 4. A snapshot showing the velocity contours during the WR stage of the evolution of the wind-blown bubble. The WR wind has broken through the RSG shell, carried the material out to the MS shell, collided with it and reflected back. This results in a very turbulent interior within the cavity.

last 0.5 million years or so, this ratio increases to 4-5%. It decreases in the RSG phase as expected, because the RSG region does not stretch too far out. But when the W-R wind impacts the RSG shell and breaks it apart, mixing the material into the surrounding region, this ratio increases considerably to almost 20%. At that point almost 1/6th of the kinetic energy in the interior is going into non-radial motions.

5. Discussion, Summary and Future Prospects

Turbulence implies various things to people. To many it signifies a perturbation, generally non-linear, that disrupts a smooth background flow. Elmegreen and Scalo (2004) in a comprehensive review article, define it as “non-linear fluid motion resulting in the excitation of an extreme range of correlated spatial and temporal scales.” Unstable regions caused by the growth of hydrodynamical instabilities can disrupt the smooth background flow, sometimes referred to as turbulent behavior. Turbulence can also mean

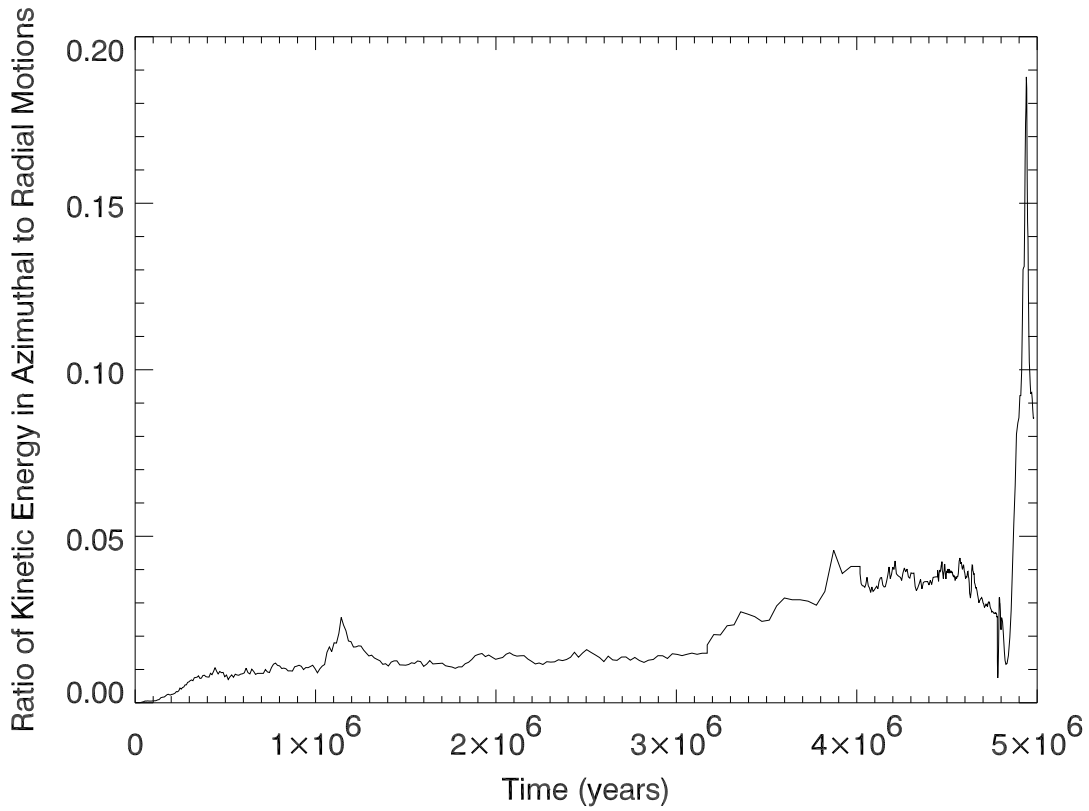


Figure 5. The ratio of energy in non-radial motions to that in radial motions in the interior low density cavity, throughout the stellar lifetime. The ratio starts out low (0.01-0.02) as expected, increases over the MS stage to 0.04-0.05, drops in the RSG stage and then increases significantly, to almost 0.2, in the WR phase.

the complete disruption of the flow, for example a radial flow showing considerable non-radial motions, the presence of vortices and strong inhomogeneities in the flow properties. Turbulence generally implies a high Reynolds number, but the Reynolds number in simulations is many orders of magnitude below those seen in nature.

In this paper, we have investigated the turbulence generated during the evolution of a wind bubble around a massive star. We find that turbulence within the interior is reflected in the formation of vortices during the star’s main-sequence phase, and in the growth and evolution of Rayleigh-Taylor instabilities during the RSG and W-R phases. The turbulence reaches a maximum close to the end of the star’s lifetime, when the WR shock completely breaks up the fragmented RSG shell, carries the material out till it impacts the MS shell and reflects back from it. The instabilities in the RSG and WR phases, the fragmentation of the RSG shell by the WR wind and the resultant uneven bounce from the MS shell lead to the turbulent interior of the bubble at the end of the star’s life, when it will collapse in a massive SN explosion. The resulting SN shock wave will expand into this turbulent medium.

The amount of energy expended in non-radial, turbulent motions is important for astrophysical purposes. The internal energy in the hot shocked wind region leads to a very high temperature in that region. The standard Weaver et al. (1977) model predicts a temperature of about 10^7 to 10^8 K, which would result in strong diffuse X-ray emission. However, very few windblown nebulae are seen in diffuse X-ray emission (Chu et al. 2003, 2006; Wrigge et al. 2005). One suggestion is that the amount of emitting material is very low, as the densities in the interior are very low. While that is a possibility, it still is insufficient to explain the very low temperatures that are seen, on the order of 1.5×10^6 K. This suggests that some entity is reducing the temperature within the bubbles. If the post-shock kinetic energy were used up in turbulent motions and not available as internal energy, then this would reduce the temperature. However this would require a much larger percentage of the energy to be expended in turbulent motions than we observe. Thus turbulence alone can certainly not resolve this problem. However it is possible that turbulence, along with thermal conduction, mixing and hydrodynamical instabilities and other factors may all contribute to lowering the internal temperature.

Besides its importance in the dynamics of the wind-bubble itself, the turbulence has a significant impact on the evolution of the subsequent SN shock wave, as comprehensively shown in Dwarkadas (2007b). The interaction of the SN shock wave with the turbulent medium, and interaction with high-density clumps, results in wrinkling of the shock wave, as some parts get compressed while others expand faster. The corrugated shock then impacts the main-sequence shell over a period of time rather than all at once. Each impact will cause an increase in the optical and X-ray emission from the source. Therefore this interaction will cause the dense shell to brighten at different points at different times, giving a “Christmas-lights” appearance. Such a phenomenon, of bright spots appearing around a ring (rather than a shell) due to a SN shock front impacting it has been seen in SN 1987A. Although these simulations are by no means intended to explain SN 1987A, our simulations do provide a reasonable guide to at least deciphering some of what may be going on in SN 1987A. Further simulations are urgently needed to confirm the existence of the turbulent interior in wind blown bubbles around stars of various initial mass undergoing various evolutionary scenarios.

The simulations presented in this paper were carried out on a two-dimensional grid. It is well known that 2D turbulence has very different properties from 3D turbulence. 2D turbulence results in an inverse cascade in energy, as opposed to 3D turbulence, where energy cascades to lowest scales (Smith & Yakhot 1997; Danilov & Gurarie 2000; Delbende et al. 2004; Scalo & Elmegreen 2004; Bruneau et al. 2007). It has been shown that 2D turbulence results in a clustering of vortices which may be long-lived, and the behavior is not reproduced in 3D. Our simulations do show these aspects, although we do not see merging of vortices except near the inner shock region. All these results, though well documented, are based on experiments conducted for 2D incompressible flows. Our simulations deal with 2D axially symmetric compressible turbulence. It is not easy to decide to what extent the results will carry over, although undoubtedly they will be applicable at some level. Therefore the formation of the vortices in the main

sequence phase, and the turbulent nature of the shocked wind in that phase, may be questionable. In the later phases, the formation and growth of the R-T fingers will still occur. Their length and structure will be different in the 3D calculations as compared to the 2D ones, but these differences are quantitative, rather than qualitative.

In the final analysis, it is clear from Fig. 5 that the essential result, of the turbulence within the bubble at the end of the star's lifetime, is not dependent on the main-sequence evolution so much as the post-main sequence phases. The formation of instabilities, and in particular the collision of the W-R wind with the RSG wind, the fragmentation of the RSG shell, and the impact with the MS shell to give the mixing and stirred up interior, is as likely to occur in 3D as it did in 2D, although the quantitative results may be slightly different. We therefore assert that the important qualitative results presented herein will still prove robust in 3D simulations. We are currently preparing 3D runs using the astrophysical hydrodynamics code FLASH (Fryxell et al. 2000) with which we will test this assertion, and will report those results in a future paper.

Acknowledgements: VVD is supported by award # AST-0319261 from the NSF. I am grateful for support provided by the TMBW07 organizing committee that enabled me to attend the conference. I would like to thank the conference organizers, and especially Dr. Abarzhi, for an excellent meeting in a beautiful location.

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